ACP8-GA-2009-233816
SART-TN 006/2011

FAST20XX

Future high-Altitude high-Speed Transport 20XX

Collaborative Project:
Small or Medium-Scale Focused Research Project

Theme 7: TRANSPORT

Deliverable Reference Number: D3.1.1.2
Deliverable Title: Report on trajectory analysis and optimization of the nominal flight trajectory and sensitivities

Due date of deliverable:

Actual submission date:

Start date of project: 1st of December 2009

Duration: 36 months

Organisation name of lead contractor for this deliverable:

Revision #:

Project co-funded by the European Commission within the Seventh Framework Programme		
Dissemination Level		
PU	Public	
PP	Restricted to other programme participants (including the Commission Services)	X
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

APPROVAL

Title	**issue**	revision
optimization of the nominal flight trajectory and sensitivities	1	0

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Table of contents

List of Figures

List of Tables

Nomenclature

Acronyms

AoA	Angle of Attack
LOX	Liquid oxygen
LH2	Liquid hydrogen
SART	Space Launcher System Analysis

Roman Symbols

T	temperature [K]
t	tons
P	pressure [Pa]
M	Mach number
n	g-load [g]
V	Velocity

Greek Symbols

Δ	delta
ρ	density [kg m^{-3}]
α	angle of attack [^{o}]

Superscripts and subscripts

1	value 1
2	value 2
z	z-direction

1. **Executive summary**

1.1 Scope of the deliverable

This deliverable presents work done on the optimization of the nominal flight (a flight from Sydney to Western Europe). Optimality is measured with respect to the total take-off mass of the SpaceLiner. The main parameter is therefore propellant mass. A trajectory resulting in lowest propellant requirement (low delta V) is considered the most optimal.

Before the start of FAST20XX an optimized trajectory was found which was based on the known fact that a skip trajectory maximizes the range of a re-entry vehicle and that maximizing the glide ratio will also increase the range. Also, the trajectory followed the orthodrome which gives the minimum distance between Sydney and Western Europe. The skipping was achieved by always flying at that angle of attack which gives maximum glide ratio. Because of the excess velocity when the orbiter enters the atmosphere the generated lift will carry the orbiter out of the atmosphere again.

More detailed trajectory optimization was carried out by ASTOS, which showed that some changes to this trajectory are of advantage for the overall SpaceLiner concept.

This report will present 4 trajectories. The first is the initial trajectory found by DLR-SART. This will be followed by a trajectory found by ASTOS which follows the same groundtrack as the DLR-SART trajectory. This means that the azimuth at lift off is fixed at the value used by SART.

Finally, two trajectories found by ASTOS will be presented in which this azimuth was released. In one of these two trajectories, skipping was not allowed. Releasing the azimuth resulted in a more northerly trajectory which significantly reduced the required propellant mass. An overview of these trajectories together with the required propellant mass is given in Table 1.

For more details on the ASTOS trajectories, the reader is referred to [1].

trajectory	Propellant mass [t]	Remarks
SART original	987	Shortest distance along great circle (fixed initial azimuth)
ASTOS original	975	Shortest distance along great circle (fixed initial azimuth)
ASTOS min prop (skipping)	932	initial azimuth released
ASTOS non skipping	935	initial azimuth released

Table 1. Comparison of propellant mass for all trajectories presented in this report

1.2 Results

Optimisation of the reference trajectory carried out by ASTOS indicated that a more northward trajectory results in a lower delta V requirement (and therefore lower required propellant mass), even though the flight distance along this route is not minimal. This is explained by the fact that the following the shortest flight distance results in a more westbound flight, where the velocity component against the rotation of the earth is higher. This results in significant loss of performance.

The new, northerly trajectory saves 55 tons (5.6%) propellant mass, as shown in Table 1. It is also shown that although a skipping trajectory results in the minimum propellant mass, the improvement is only marginal compared to a non-skipping flight. A skipping trajectory results in more severe thermal loads and the marginal propellant savings are lost in extra TPS mass. Additionally, a no skipping flight is beneficial for passenger comfort. Therefore, there is no reason to stick to the skipping so the new reference trajectory is the northerly, no skipping trajectory.

1.3 Forms of integration within the workpackage and with other WPs

SpaceLiner aerodynamics and masses obtained in WP 3.1.1. together with the trajectory model were delivered to ASTOS as an input for WP 3.1.2.

2. Introduction

The SpaceLiner is a completely rocket powered spaceplane designed for suborbital, point-to-point passenger transportation. The SpaceLiner reference mission is the westbound flight from Sydney to Western Europe, chosen because it is the longest intercontinental distance. The SpaceLiner is designed to transport 50 passengers and two pilots along this route. The take-off configuration exists of two stages, a booster stage and a second stage containing the passengers which is referred to as the “orbiter” (note that is not really an “orbiter” as it does not reach orbital velocity, but conditions are very close to that of orbital flight). The SpaceLiner takes off vertically to save mass otherwise needed for for example a takeoff gear. An acceleration limit of 2.5 g in the axial direction has been set during take-off, which is achieved by throttling of the engines. Landing takes place horizontally, similar to the Space Shuttle. As long as the booster and orbiter are attached, crossfeeding between booster and orbiter is foreseen. After stage separation the orbiter accelerates further until all the propellant has been used. The remaining part of the flight is powerless. More information on the SpaceLiner concept can be found in [2].

A key requirement of the SpaceLiner is that it should be a completely reusable system. This means that also the booster must be returned safely and therefore a winged booster is used. After reentry of the booster it could fly back to the launch site if it is equipped with airbreathing engines. Another possibility is a method called “in-air capturing”, where an airplane equipped with a towing cable would capture the booster in mid air and two it back to the launch site. The big advantage of this method is that no airbreathing engines are needed on the booster. This saves a lot of mass and makes the complete system much lighter.

Engine performance of the SpaceLiner is deliberately kept lower than today’s highest performing engines such as the SSME. By using lower combustion chamber pressures the reusability of the engines is increased, which is surely important for a commercial concept such as the SpaceLiner. It is not exactly know today by how much reusability increases and additional measures might be nescessary. Engine data is given in Table 2. The nozzle expansion ratio has been optimized for each stage.

	Booster	Orbiter
Number of engines	9	2
Mixture ratio	6:1	6:1
Chamber pressure [MPa]	16	16
Mass flow per engine [kg/s]	384.5	384.5
Specific impulse in vacuum [s]	437.6	448
Specific impulse at sea level [s]	388.4	360.4
Thrust in vacuum per engine [kN]	1650.6	1689.8
Thrust at sea level per engine[kN]	1465.0	1359.4

Table 2. Engine data

To reduce take-off mass and size the trajectory has been optimized for maximum range. Because the size of a rocket propelled vehicles is very sensitive to the required ΔV, achieving maximum range has been priority throughout the SpaceLiner design (a trajectory optimized for maximum range will reduce the required ΔV). Optimizing the range results in a skipping trajectory for the powerless flight phase of the orbiter, where the angle of attack (AoA) is chosen such that it gives the highest L/D. This AoA changes with the Mach number, so that the trim of the orbiter has to be adapted throughout the flight to fly at optimum AoA.

A downside of this skipping trajectory is the high heat load encountered during skipping. Heat loads are much higher than for example a re-entry of the Space Shuttle, so passive radiation cooling is not an option for the SpaceLiner if the skipping trajectory is to be maintained. For passenger comfort, a limit on the acceleration in normal direction has been set to 1.5 g during the skipping flight.

Before FAST 20XX started, the SpaceLiner concept had already been investigated. The resulting concept of this preliminary analysis is referred to as SpaceLiner2 (SL2**)** and will be described in the next chapter. The following chapters will then discuss adaptations made to this concept in the frame of FAST 20XX. The results of other analyses done during FAST 20XX, such as investigation into different routes, will also be presented.

2.1 The SL4 version

Over time the design of the SpaceLiner has evolved. This has resulted in several different SpaceLiner versions [2]. The current situation is that the version “SL4” is the baseline within FAST20XX. As a next step in FAST20XX the SL7 will be defined and used as the new baseline, but for now it means that the trajectories presented in this document are all based on the SL4 performance. Figure 1 shows the glide ration versus AoA for different Mach numbers, including low speed sub- and supersonic values. More detailed aerodynamics can be found in [2]. There also values for lift- and drag coefficient are given, as well as required elevator deflection angle for trimming of the vehicle. Additionally, aerodynamics of the whole system (orbiter attached to booster) is given. Data on exact masses and dimensions of the SL4 are given in Table 3.

Figure 4 shows the ascent trajectory of SL4. Booster separation occurs after 221 s at an altitude of 83.7 km. Separation velocity is 3.3 km/s. MECO of the orbiter occurs 202 s later, at an altitude of 80 km and velocity of 6.7 km/s.

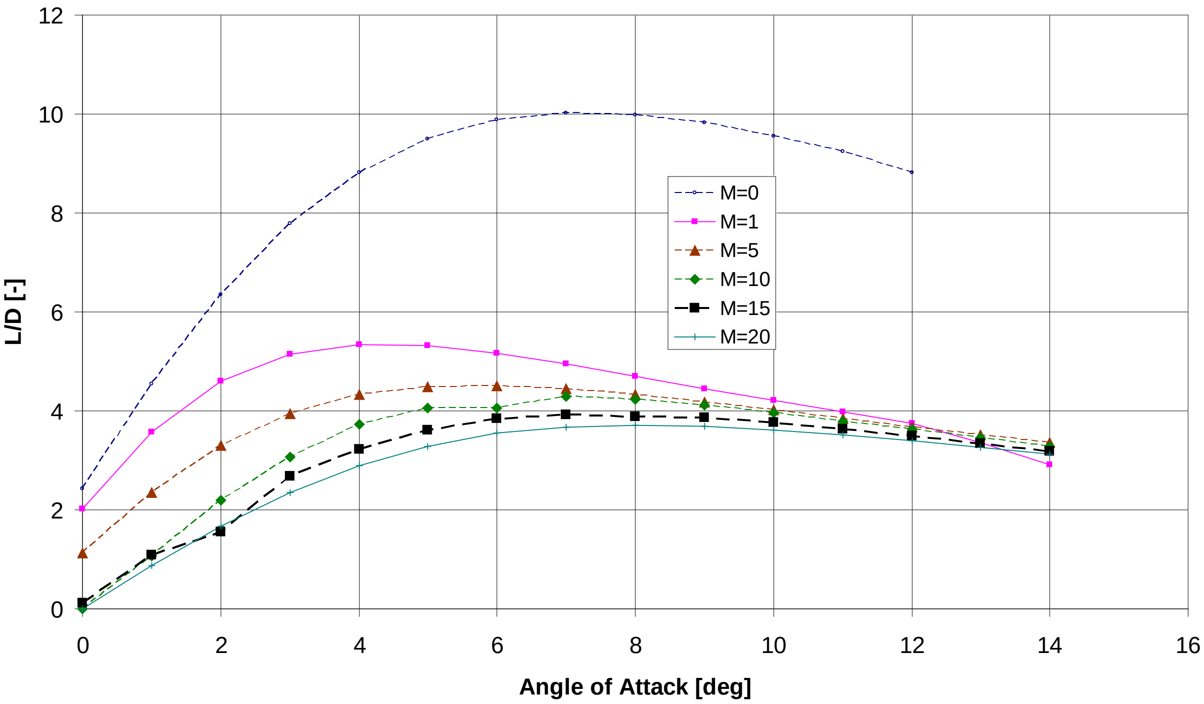

Figure 1. SL4 aerodynamics

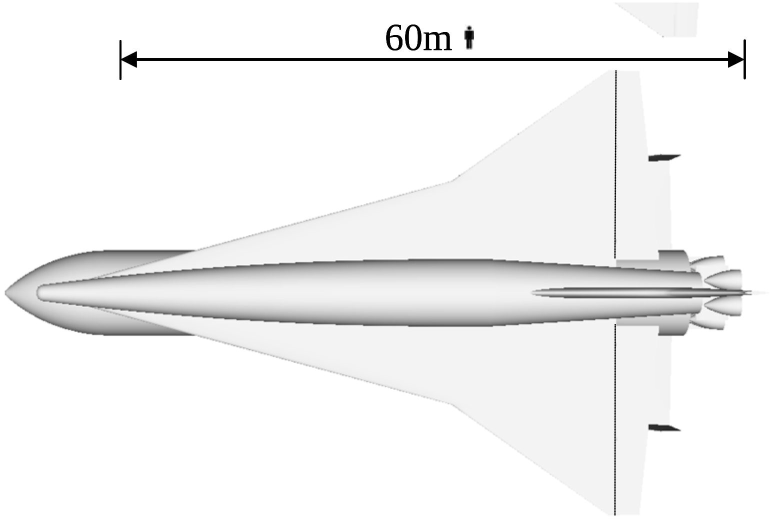

Figure 2. SL4

	GLOW Mass [kg]	Mass at burnout [kg]	Propellant mass [kg]	Fuselage length [m]	Max. fuselage diameter [m]	Wing span [m]	Projected wing surface area [m²]
Orbiter	277,934	122,934	155,000	57	6	40	955
Booster	959,855	128,199	831,656	64.3	8	25.5	325
Total	1,237,789	251,133	986,656	-	-	-	-

Table 3. SL4 masses and dimensions

3. Trajectory

3.1 Initial optimisation

As a first attempt to find the optimal trajectory the following logic was applied by the DLR-SART.

The first assumption was that the SpaceLiner should fly along a great circle connecting the start and end point over the shortest possible distance. This results in a groundtrack shown in Figure 3. The second assumption was that during the powerless flight phase, the orbiter should always fly at the optimum angle of attack (the angle of attack resulting in the highest glide ratio). This automatically results in a skipping trajectory. To make sure that the 1.5 g requirement is not exceeded during skipping, a simple control function was implemented in the trajectory tool which reduces angle of attack when 1.5 g is exceeded.

From ascent trajectory analysis it is known what the final velocity and altitude of the orbiter at MECO is. This velocity and altitude can then be used as an initial condition for the analysis of the powerless flight phase. By adapting the ascent trajectory such that different MECO conditions are reached, different initial conditions can be used for the analysis of the powerless flight phase. Adapting the ascent trajectory is done by changing the flight control parameters such as pitching rate and angle of attack. Using the different MECO conditions a parametric study can be made to find out which trajectory is the most optimal one. The most optimal trajectory resulting from this analysis is given in Figure 4. The loads during the skipping motion are below 1.3 g, staying well within the requirement of a 1.5 g maximum load. Some characteristic data regarding this trajectory is given in Table 4. MECO occurs at 80 km and a velocity 6.7 km/s.

Figure 3. Groundtrack of initial DLR-SART approach

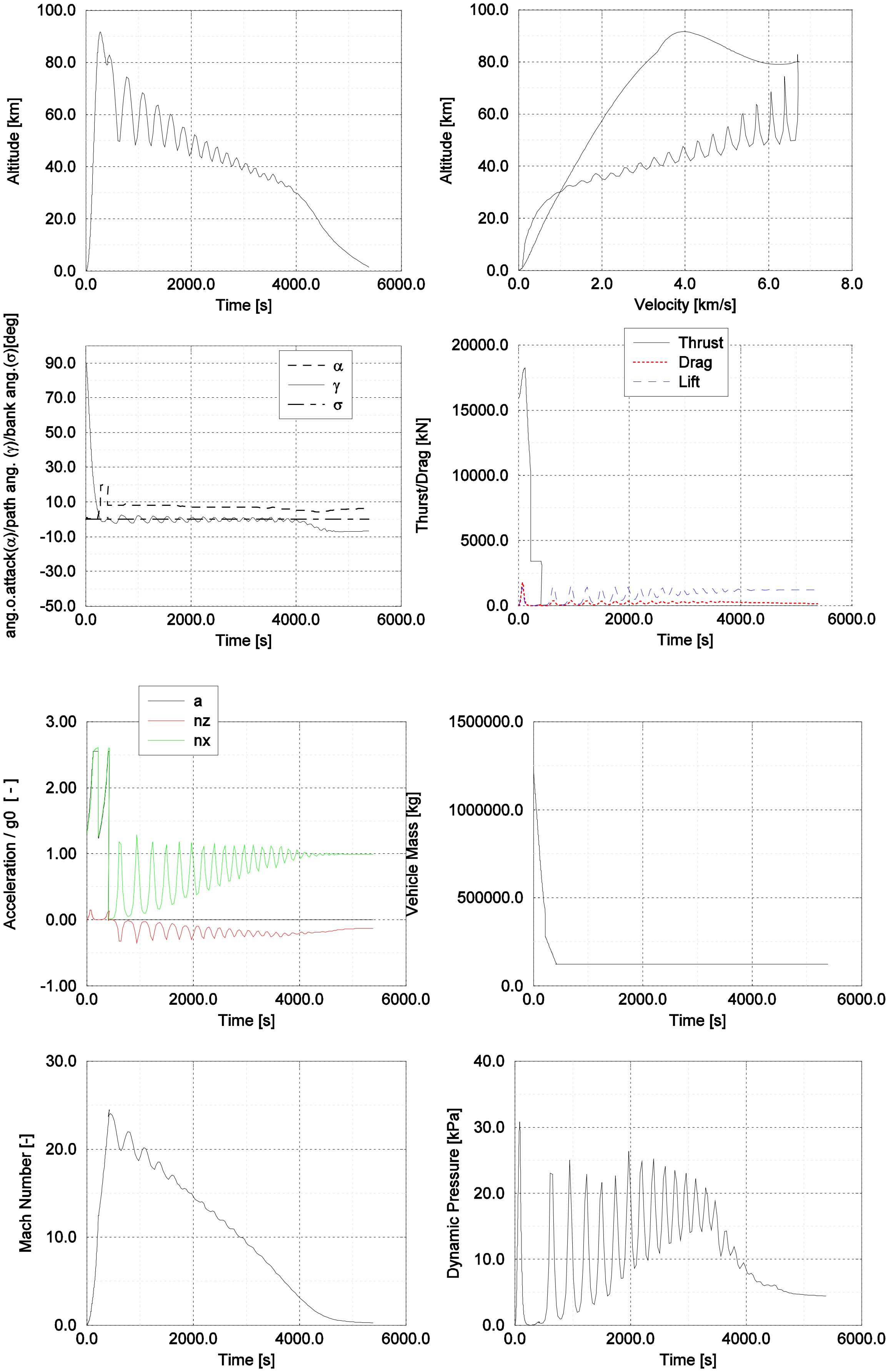

Figure 4. SL4 DLR-SART trajectory

3.2 ASTOS optimisation using same initial azimuth

Astos solutions used their software ASTOS to optimize the SpaceLiner trajectory in order to verify the DLR-SART approach and to see if there is any potential to increase performance. As a first approach the initial azimuth at lift off was fixed. This yields the same groundtrack as the DLR-SART trajectory, shown in Figure 3. ASTOS produced a trajectory which saves 11 tons of propellant (1.1%). An interesting fact is that the ASTOS results give a much lower separation altitude of 51 km compared to the 84 km obtained by DLR-SART (see Table 4 and Figure 10). Also the orbiter MECO altitude of 69 km is lower than the 80 km which resulted from the SART approach. The trajectory output can be seen in Figure 5.

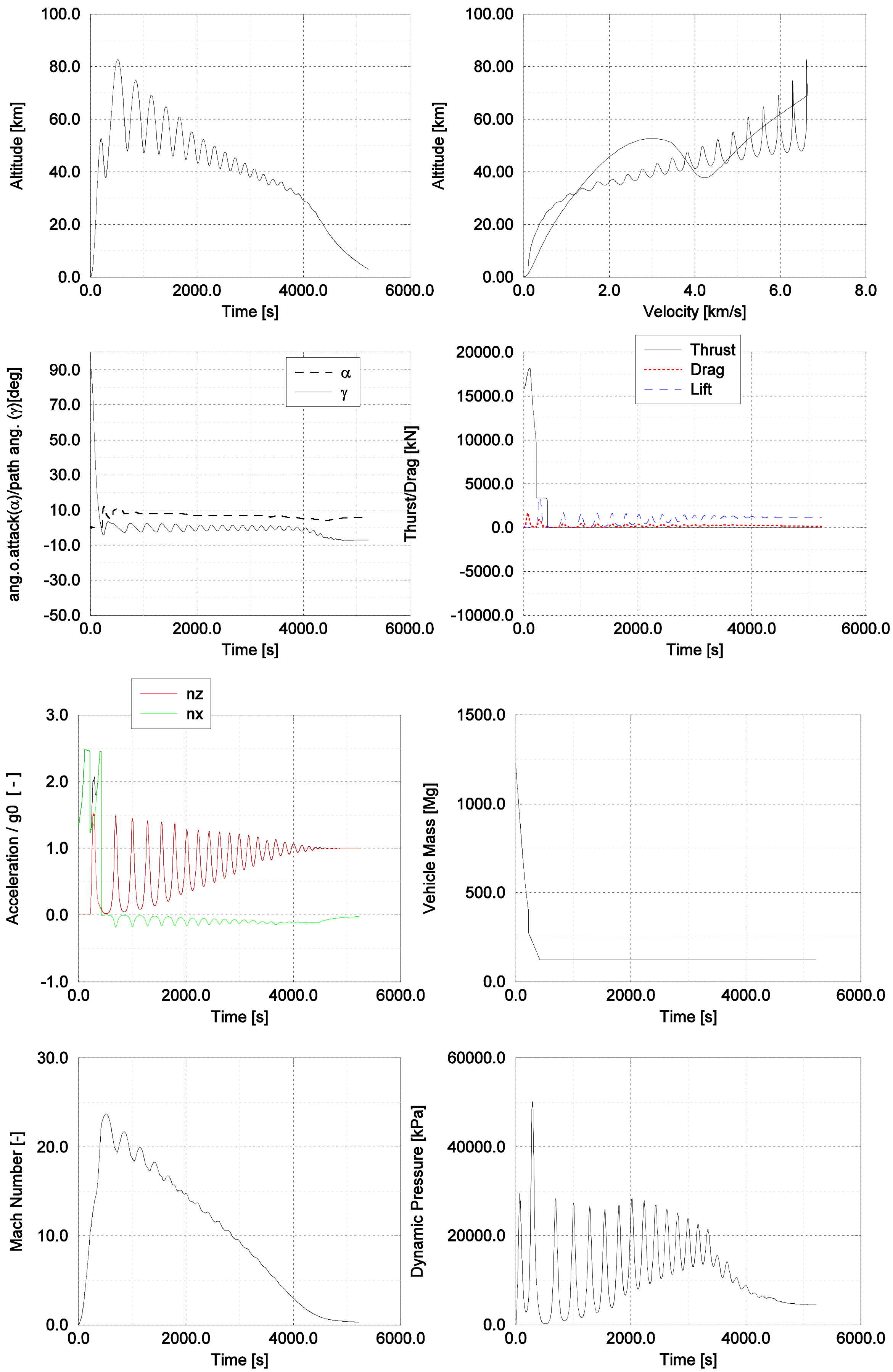

Figure 5. SL4 initial ASTOS trajectory

3.3 ASTOS minimum propellant trajectory

In a second approach the initial azimuth at lift off was released. ASTOS found a much more northerly trajectory which saves 54 tons of propellant (5.5%), see Table 4. The groundtrack of this trajectory is shown in Figure 6. It shows two cases, a skipping trajectory (discussed in this section) and a no skip trajectory (discussed in next section). The actual flown distance along this trajectory is longer but the propellant savings can be explained by the fact the velocity component against the rotation of the earth is smaller. This results in a more efficient trajectory.

Figure 7 show the complete trajectory output of the ASTOS trajectory with the released initial azimuth and with skipping. This trajectory results in the lowest required propellant mass.

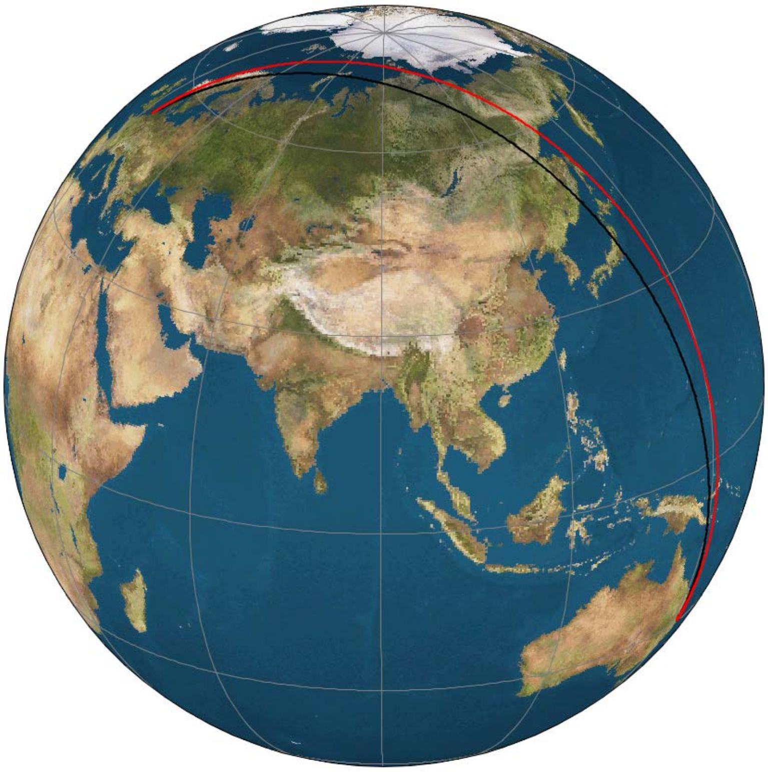

Figure 6. Groundtrack of ASTOS trajectory with initial azimuth released. The black line represents the skipping trajectory and the red line the no skipping trajectory.

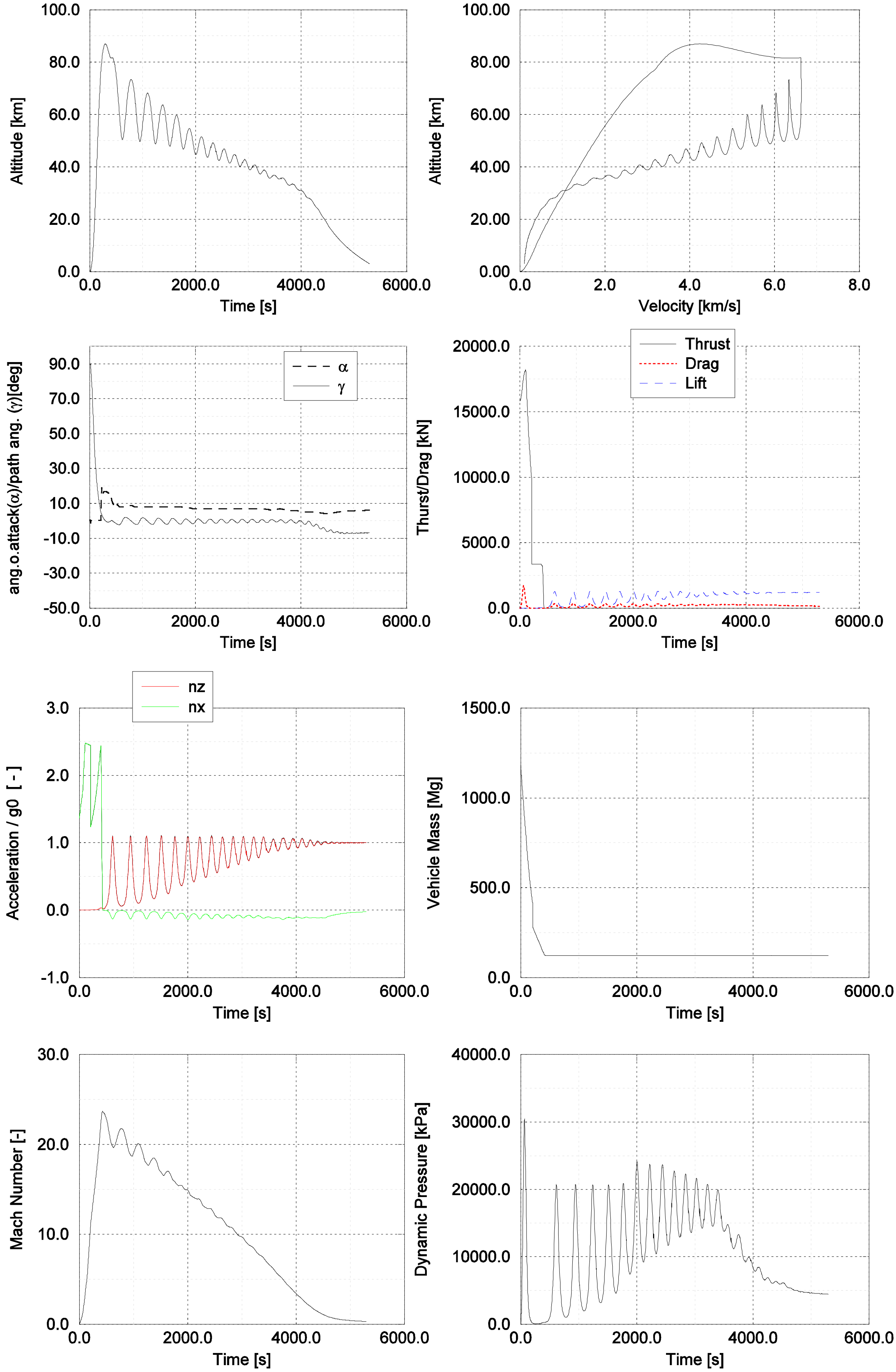

Figure 7. SL4 ASTOS trajectory with skipping and initial azimuth released.

3.4 ASTOS non skipping trajectory

Another trajectory was investigated which gets rid of the skipping. Although it is known that skipping results in the most optimal trajectory in term of propellant mass, a no skipping trajectory would be beneficial for passenger comfort. It is therefore interesting to see what the impact on the propellant mass would be when skipping is not allowed. The no skipping trajectory requires 3 tons additional propellant compared to the skipping trajectory, see Table 4. This propellant increase is only very marginal (0.3%) and so the question rises if passenger comfort should be chosen over marginal propellant savings. The no skipping trajectory has another major advantage. The maximum heat flux on the orbiter is much less as shown in Figure 8. The integral heat load remains approximately the same but maximum heat flux values are much lower allowing the use of lighter TPS materials, saving approximately 14 tons. This is shown in [4]. The 3 tons of propellant savings for the skipping trajectory are lost in a much heavier TPS and as such the skipping trajectory is not an interesting option anymore.

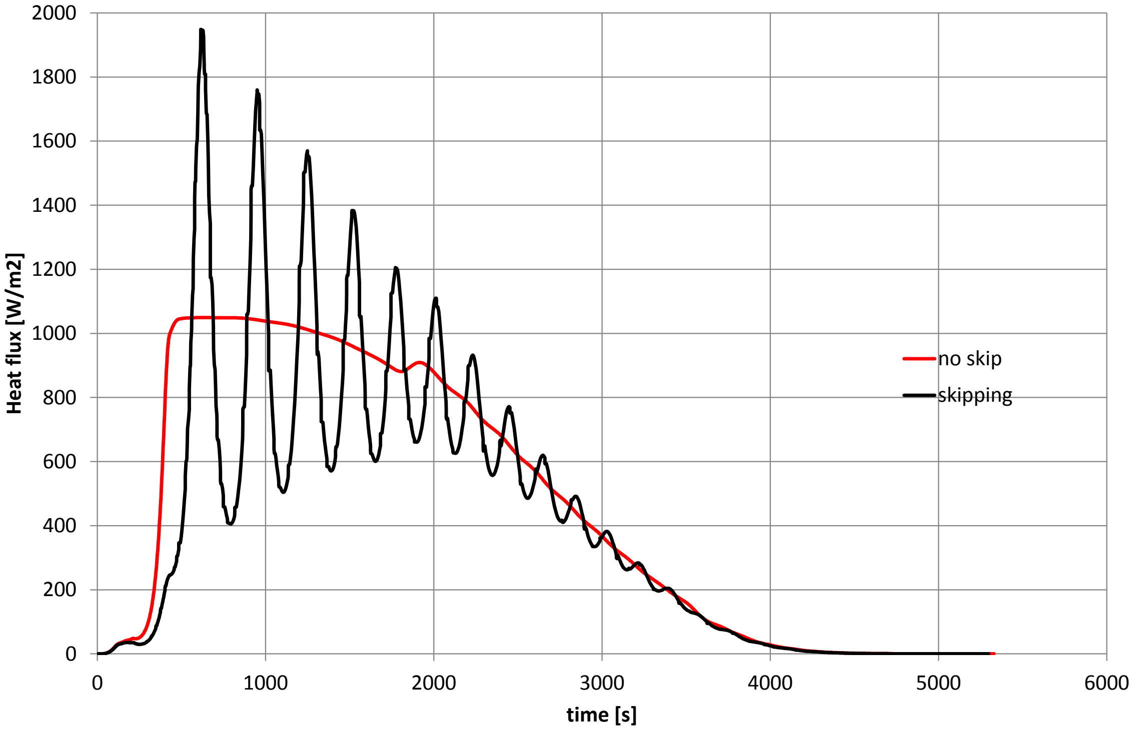

Figure 8. SL4 nose heat flux of skipping and no skipping trajectory.

The no skipping trajectory presented here in Figure 9 is therefore chosen as the new reference trajectory for the SpaceLiner.

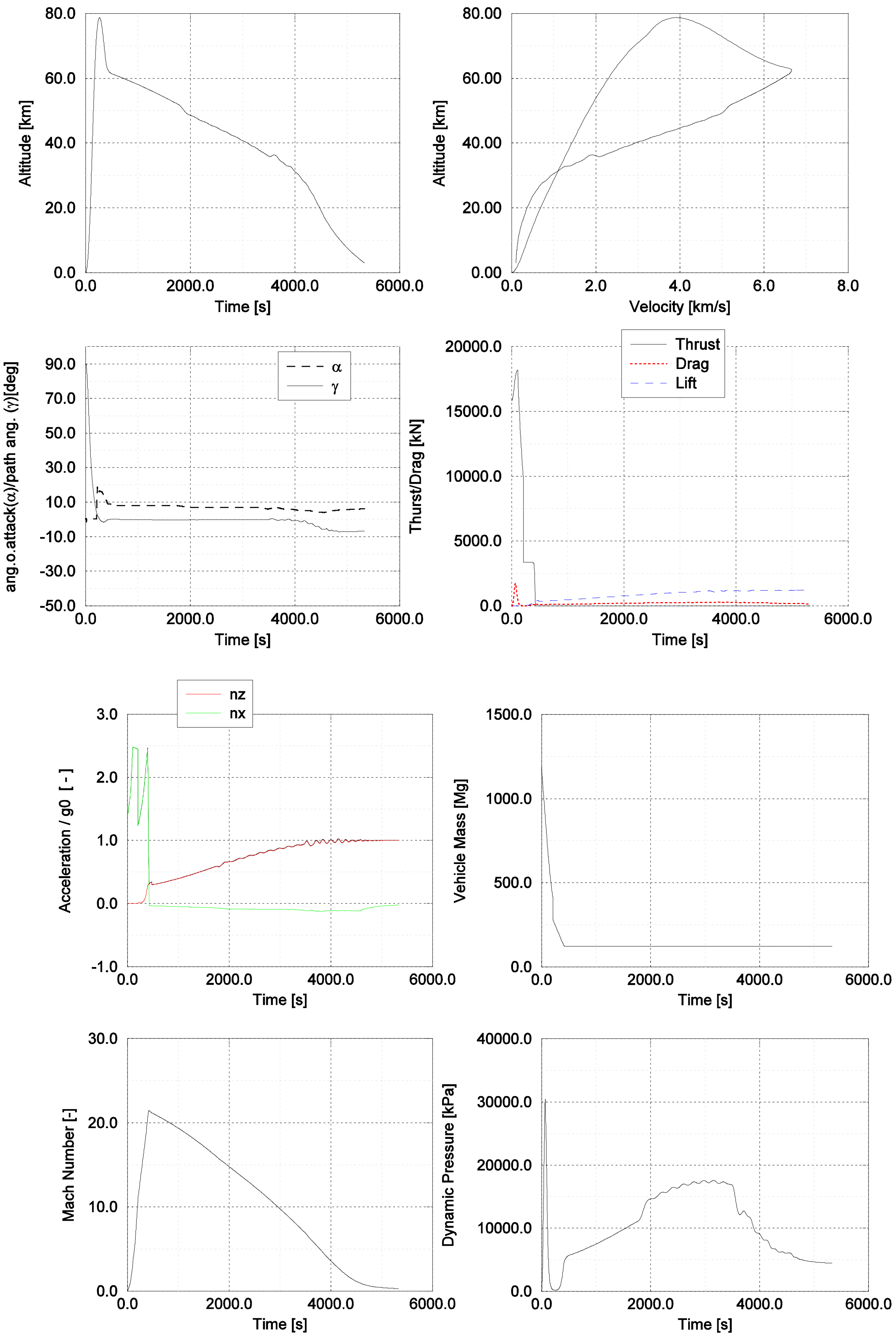

Figure 9. SL4 ASTOS trajectory without skipping and initial azimuth released.

3.5 Trajectory comparison

Characteristic trajectory data is shown in tabular form in *Table 4*. All four trajectories are compared with each other in Figure 10. In this figure the diamond shapes indicate booster separation and the dots indicate orbiter MECO. As can be seen for the original ASTOS trajectory the booster separation occurs much lower than for the others cases. In case of the ASTOS non skipping trajectory, orbiter MECO occurs low compared to the other cases.

	original DLR-SART trajectory	original ASTOS trajectory	ASTOS min prop (skipping)	ASTOS non skipping
Altitude at sep.	84 km	51 km	77 km	73 km
Velocity at sep.	3.3 km/s	3.45 km/s	3.19 km/s	3.22 km/s
Altitude at MECO	80 km	69 km	82 km	63 km
Velocity at MECO	6.7 km/s	6.64 km/s	6.62 km/s	6.66 km/s
Booster prop mass	831 tons	821 tons	776 tons	779 tons
Orbiter prop mass	155 tons	154 tons	156 tons	156 tons
Total prop mass	986 tons	975 tons	932 tons	935 tons

Table 4. Trajectory data

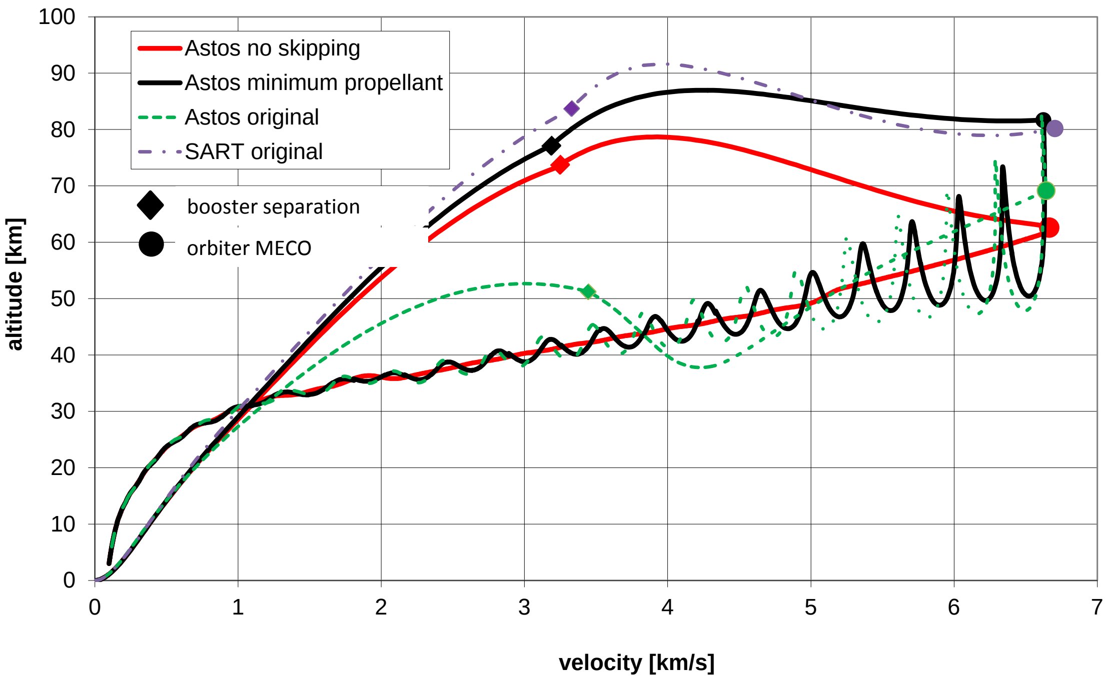

Figure 10. Comparison of all four trajectories

4. Sensitivities

A lot of effort has been put into maximizing the glide ration of the orbiter in the hypersonic region. An analysis has been performed to give a feeling of how sensitive the system is to changes in the glide ratio. This analysis was done using the initial DLR-SART trajectory, but it is expected that the results are also applicable to the other trajectories presented in this report.

The nominal glide ratio has been changed by adapting the lift coefficient with a certain percentage. From this a new glide ratio follows and the required velocity to reach the unchanged destination has been redetermined using this new glide ratio. All other MECO conditions were assumed fixed (for example the MECO altitude was assumed fixed at 80 km). Results are presented in Figure 11. The results are fitted with a second order polynomial trendline. The dotted line represents the orbital velocity. For glide ratios lower than 30% of the nominal value the required velocity is higher than the orbital velocity. The fact that the required velocity must be higher than the orbital velocity is explained by the fact that drag still plays a significant role at the altitude the SpaceLiner flies.

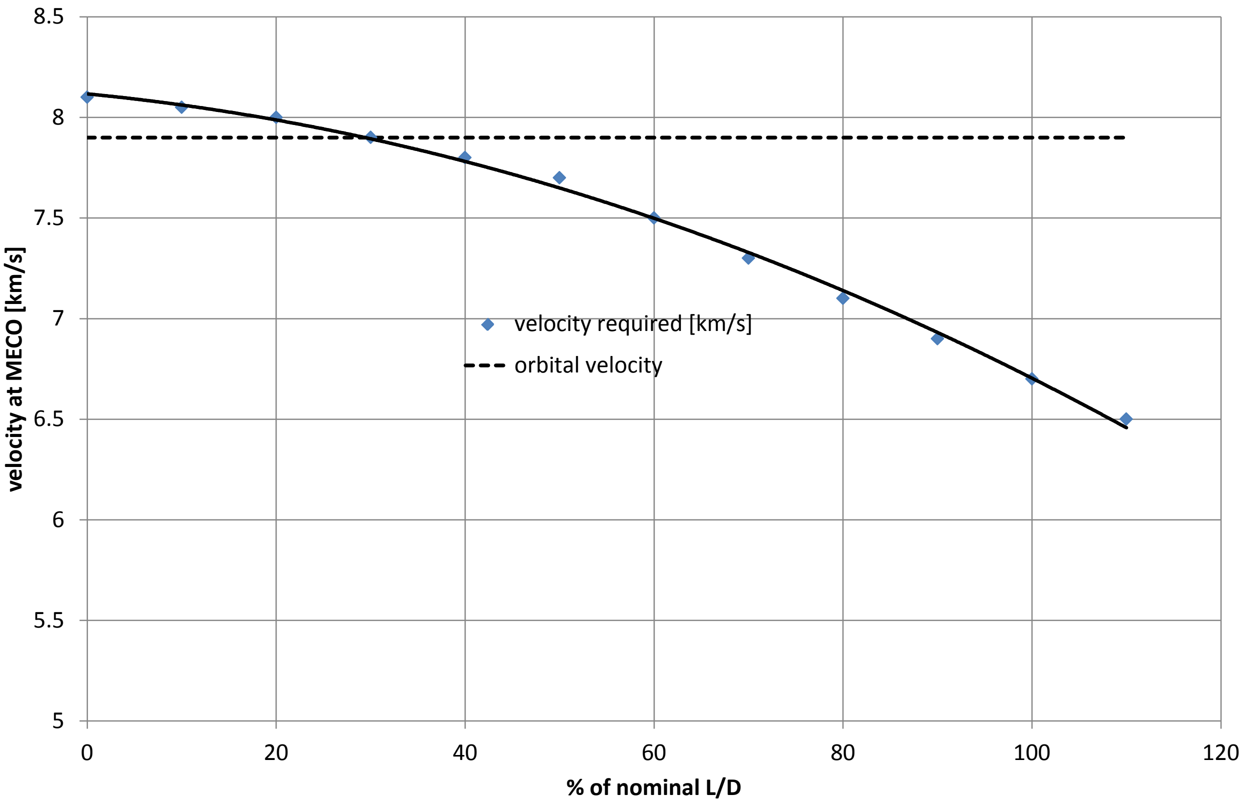

Figure 11. Sensitivity of required velocity versus glide ratio

Figure 12 gives the sensitivity of the range on the glide ratio of the orbiter. The nominal glide ratio has been changed by adapting the lift coefficient with a certain percentage. MECO conditions such as velocity and altitude were set to the nominal values (*Table 4*) and were kept constant. As can be seen an approximately linear dependency between range and glide ratio exists.

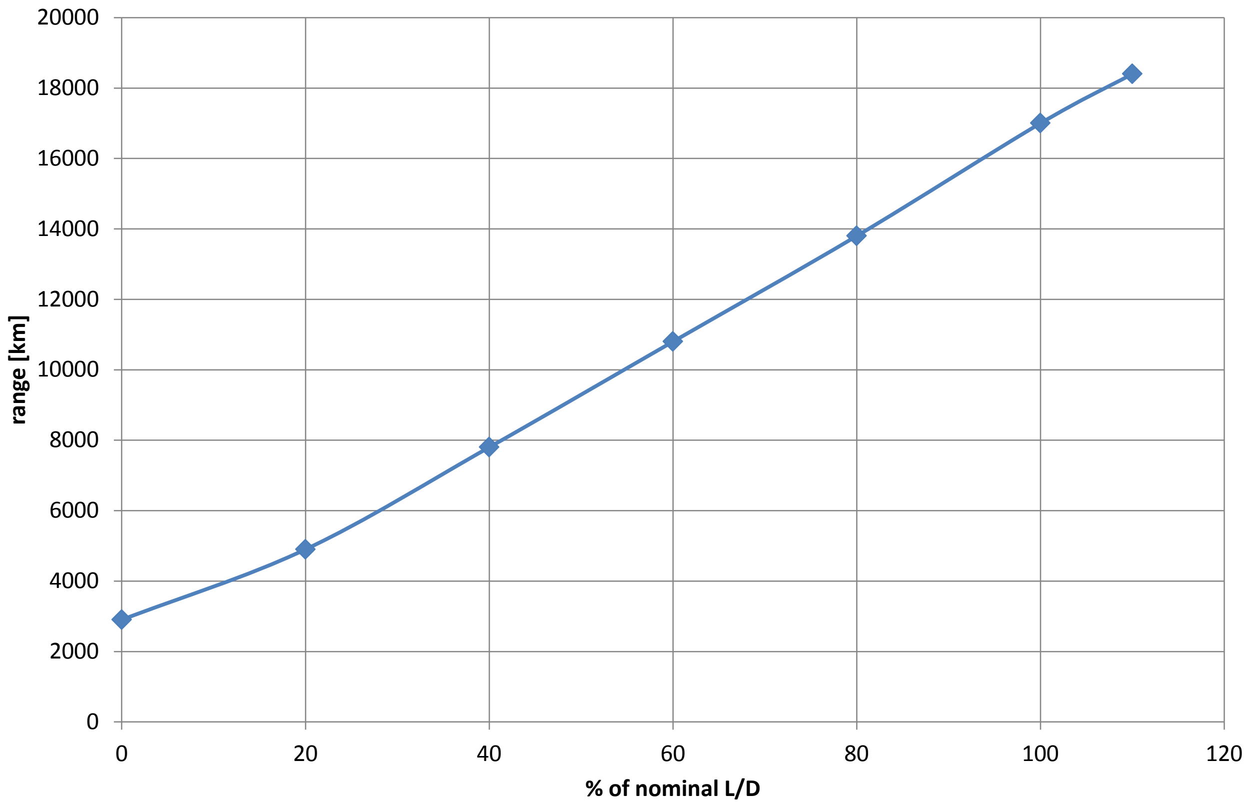

Figure 12. Sensitivity of range versus glide ratio. MECO conditions are assumed equal for each point.

An estimation of the influence of the glide ratio on the total mass at lift off can be made using the rocket equation. Because of the two staged system, the rocket equation has to be written as follows:

$$\Delta v = c_1 \ln\left(\frac{m_{i,1}}{m_{f,1}}\right) + c_2 \ln\left(\frac{m_{i,2}}{m_{f,2}}\right) \tag{1}$$

In this equation Δv includes the required MECO velocity and the velocity losses (drag loss, gravity loss and thrust loss). For the calculations presented here, the losses are assumed to remain constant. The first term of this equation describes the first phase till the separation point. The second term describes the second phase to orbiter MECO. The values c_1 and c_2 are the averaged nozzle exit velocities during the first and second phase, respectively. Averaged values have to be used because the specific impulse changes with altitude. Also, during the first phase the booster and orbiter engines are both burning but they have slightly different specific impulses, so this is reflected as well in in the average value. The values m_i and m_f represent the initial mass and final mass at burnout, respectively. The subscripts 1 and 2 indicate the first and second phase, respectively.

The orbiter is left unchanged so the second term remains constant. The first term includes the booster masses. For this analysis, the booster mass at burn out is assumed constant. This approximation is only valid when changes Δv only lead to small deviations in the total mass of the booster. If deviations are large this means the booster has to be made bigger to fit in the additional propellant and thus the structural mass would increase. Constant values used in the rocket equation are given in Table 5.

Booster structure mass [t]	128
Orbiter structure mass [t]	123
orbiter propellant mass [t]	155
c_1 [m/s]	4184
c_2 [m/s]	4400
Δv loss [m/s]	1566

Table 5: Values for rocket equation

The results of the rocket equation are presented in Figure 13. In case of a change in aerodynamics, Figure 11 can be used to establish the new orbiter MECO velocity required to fly the mission. The impact on the lift off mass can then be estimated by using Figure 13. As explained, in case of large changes in the MECO velocity, Figure 13 has to be used with caution.

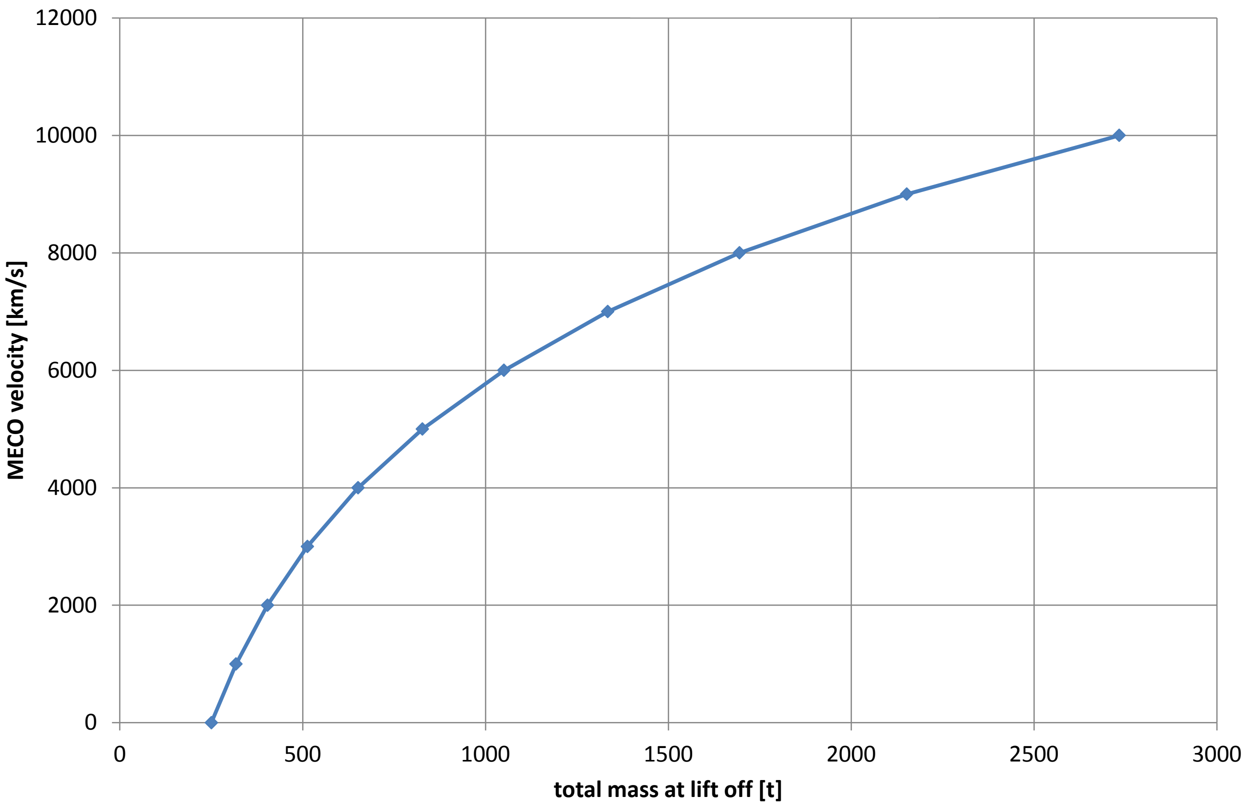

Figure 13. Impact of orbiter MECO velocity on lift off mass.

5. Conclusions

The optimisation procedure initially followed by DLR-SART for the Sydney-Western Europe mission resulted in a required propellant mass of 986 tons. The trajectory involved a skipping motion, where n_z was below 1.3 g. The trajectory followed the shortest possible distance between Sydney and Western Europe.

ASTOS optimisation has resulted in a significant improvement of the trajectory. The trajectory follows a more northerly route which increases the distance to be travelled but because the velocity component against earth's rotation is reduced the trajectory is actually more efficient. This new route saves 54 tons of propellant (5.5%). Also, ASTOS optimisation showed that flying a skipping trajectory only saves 3 tons of propellant compared to a no skipping trajectory. The maximum heat flux during the no skipping trajectory is much lower, allowing the use of lighter TPS materials, saving approximately 14 tons. This outweighs the 3 tons of extra propellant mass. Also a trajectory without skipping is better for passenger comfort. This means that the no skipping trajectory is the new reference trajectory for the SpaceLiner.

6. References

[1] Cremachi, F.: FAST20XX deliverable D3.1.2.1 Mission Analysis Document

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